A Co-integrated Silicon-Based Electronic-Photonic Wideband, High-Power Signal Source


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Abstract: A novel co-integrated electronic-photonic distributed photo-mixer-amplifier is presented that improves the bandwidth and gain of the system. An RF signal with an output power of 10 dBm across the bandwidth of 50 GHz was achieved.

1. Introduction

A wideband and high purity signal source is a critical component for variety of applications, including communications, sensing, radar and software-defined radio. Electronic signal sources provide narrow bandwidth with relatively poor phase noise performance which can limit the performance of the entire system. Photo-mixing is a common technique for generating wideband RF signals from the optical sources [1]. Two light signals with a small offset in wavelengths (frequency offset) are coupled into a photodetector. The photodetector acts as a mixing component to generate an RF current with a frequency equal to the frequency difference between the input optical signals. The generated signal using this technique can be tuned in extremely wide frequency range with low phase noise, however, the power of the generated signal is often low and requires extremely high input optical power for most of the practical applications. Providing high input optical power can be bulky and expensive, with low efficiency. By advancing the technology, the integration of electronic and photonics parts has now become feasible facilitating a compact implementation of these types of systems. A wideband and high-power electrical amplifier can be designed following the photo-mixer to boost the power of the generated signal and alleviate the need for high power optical amplifier, however, achieving both high power and wide bandwidth at the same time is challenging.

A distributed (travelling wave) amplifier is a common technique for realizing high power and wideband amplification [2],[3] (Fig. 1.). Several amplifier stages are distributed across a long transmission line. The parasitic capacitances of the amplifiers are absorbed in these T-lines to enhance the effective bandwidth of the system. The input parasitic capacitance of typical amplifiers are several times larger than the output capacitance, and thus the bandwidth of the input T-line is typically the main limiting factor for the bandwidth of the entire circuit. Therefore, the input signal quickly fades away while propagating on lossy and capacitive input line. In addition, to accommodate a linear operation of photodetectors for high power optical input signals, several photodetectors in parallel are required. The parasitic capacitance of these devices can further degrade the bandwidth of the system.

Fig.1. Schematic of a conventional distributed amplifier.

2. Proposed Architecture

The approach proposed here utilizes a novel combination of signal generation and amplification to improve the bandwidth, gain, and linearity of the system, by co-designing the electronic and photonic parts in an integrated Si-based solution. Fig. 2. Shows the schematic diagram of the proposed architecture. The photo-mixing and amplification components were combined and distributed across the input line of the amplifier utilizing low-loss silicon waveguides. The optical signals are coupled to the silicon waveguide through a grating coupler. Si-based optical waveguides present significantly lower loss (1-3 dB/cm) compared to electrical T-lines. Ge waveguide-coupled photodetectors with a bandwidth of 60 GHz and the responsivity of 0.9 A/W is available on-chip and were utilized for the photo-mixing operation. In contrast to the traditional approach, where the incoming lights are mixed immediately at photodetectors and the generated RF signal is fed to the input of an amplifier, the incoming lights in
the proposed approach are distributed across several photo-mixing-amplification stages in optical domain. This technique replaces the RF signal propagation across the lossy, narrow bandwidth input T-line of the distributed amplifier with light propagation in low-loss waveguides. Several photo detectors were distributed across different stages of the amplifier to inject the signal evenly at multiple locations. Four photodetectors in parallel were designed to feed each amplifier stage. The input optical signals were divided equally between various photodetectors by utilizing carefully designed, extremely low-loss optical waveguides and MMI components at 1550 nm standard communication band. The length of the optical waveguides was designed such that the introduced additional delays equalize the delays of the travelling signals at the input and at the output of the amplifier, so that the amplified signals can add in phase at the output of the amplifier. The input signal is a travelling light in an optical waveguide, while the output signal is a travelling RF signal in an electrical transmission line. Since the group velocity of the wave propagation in silicon dielectric is higher than the group velocity of the propagation in a silicon waveguide, the shorter optical waveguides can produce the desired delays to equalize the delays introduced by long transmission lines at the output. Thus, the loss of the signal at the input is further reduced, which favors the presented approach.

Fig. 2. Schematic diagram of the proposed distributed photo-mixing-amplifier architecture. Highlighted in blue are optical waveguides.

A tree-based delay distribution network as shown in Fig. 2 was utilized for this purpose. The combination of a multiport signal injection with the availability of low-loss optical waveguides allows for the even distribution of the input signal across the amplifier stages. In contrast to the traditional distributed amplifier approach where the number of stages are limited due to significant signal attenuation while propagating through the input T-line of the amplifier, the attenuation of the input signal is significantly lower in the presented approach, and thus additional amplifier stages can be utilized for higher gain and output power beyond the achievable limits of conventional distributed amplifiers. Distributed photodiode-only circuits exist [4],[5]. However, the co-design of photo-mixing and amplification here is novel and provides additional advantages such as bandwidth enhancement of the amplifier by avoiding the low-speed input line of the amplifier. In addition, it allows increasing the gain of the system by increasing the number of stages of the distributed amplifier.

The present design utilizes eight stages of amplifiers. Each stage of the amplifier utilizes a source degenerated cascade topology with SiGe HBTs. Eight photo-mixing components, each consisting of four photodiodes in parallel were designed to directly feed each amplifier stage in the circuit. Since the input T-line is not fed by a signal source, the Z0 of the line can be chosen arbitrarily. To increase the bandwidth of the capacitively loaded input line, the Z0 of 25 ohms was chosen. On the other hand, the Z0 of the output line with higher bandwidth, was increased to 70 ohms to compensate for the gain reduction resulted from input line while providing acceptable power matching to 50 ohms at the output. Since the high-power input optical signal was divided between 32 photodiodes, the linearity limitations of photodiodes are effectively eliminated, while the parasitic capacitances of these diodes are absorbed within the input line of the amplifier without significant bandwidth degradation. Thus, the linearity of the present system is not limited by the linearity of the optical part.

2. Measurement Results
Fig. 3 compares the response of the presented system with a traditional approach, where photo-mixing diodes and distributed amplifiers are designed separately, and diodes are placed at the input of the amplifier. The bandwidth of the system is considerably enhanced in the approach proposed here. Fig. 3 also shows the measured output power compared with the simulations. An output power of greater than +10 dBm was generated from the circuit across a more than 50 GHz bandwidth. In this measurement, the output power was limited by the available input optical power. Simulations show that saturation power of the entire system can be as high as +18 dBm at the output. Measured photocurrents and output power indicate that, compared to ideal diode-only distributed circuits, the present circuit provides more than 12 dB of additional gain, and thus optical amplification can be eliminated by providing wideband electrical amplification. The amplifier draws 43 mA from a 4 V supply.

![Simulated and measured output power comparison](image)

Fig. 3. Simulated comparison of the output power between the conventional approach and the proposed architecture (left), Measured output power compared to simulation (right).

Fig. 4 shows the measured eye diagram at the output of the circuit when a 40 Gbps pseudo random data was modulated on top of the single incoming optical signal utilizing an external MZM modulator. The circuit was implemented in the 180 nm IHP-EPIC SiGe integrated photonics technology. The chip photo is also shown in Fig. 4. Table I compares the results with state-of-the-art.

![Eye diagram and die micrograph](image)

Fig. 4. Measured eye diagram at the output of the proposed system (left), Die micrograph of the proposed photonic-electronic circuit (right). The chip measures 3.2 × 1 mm².

<table>
<thead>
<tr>
<th>Reference</th>
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<th>[4]</th>
<th>[5]</th>
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<td>Distributed Amplifier-Photomixer</td>
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Table I. Comparison with state of the art.

3. References


TWPD: Travelling-wave photo diode.